

TITLE

[0001] Electrolyte for Electrochemical Cell

REFERENCE TO PRIOR FILED APPLICATIONS

[0002] This application is a continuation-in-part of U.S. Patent Application serial number (not yet assigned), filed concurrently herewith; entitled "Electrolyte System" and incorporated herein in its entirety.

[0003] This application is related to PCT application number PCT/US03/08779, entitled "Polymer Electrolyte for Electrochemical Cell" and filed March 20, 2003 which claims priority to U.S. Provisional Patent Application serial number 60/446,848, entitled "Polymer Electrolyte for Electrochemical Cell" and filed February 11, 2003. This application is also related to copending provisional application serial number 60/443,892 entitled "Nonaqueous Liquid Electrolyte" filed January 30, 2003; and to PCT/US03/02127, filed January 22, 2003; and to PCT/US03/02128, filed January 22, 2003; and to copending US application serial number 10/167,490 filed June 12, 2002, which is a Continuation-in-Part of co-pending application Serial Number 10/104,352, filed March 22, 2002. Each of the patent applications mentioned in this paragraph is incorporated herein in its entirety by reference, including all disclosures submitted therewith.

GOVERNMENT LICENSE RIGHTS

[0004] This invention was made with United States Government support under NIST ATP Award No. 70NANB043022 awarded by the National Institute of Standards and Technology (NIST). The United States Government has certain rights in this invention pursuant to NIST ATP Award No. 70NANB043022 and pursuant to Contract No. W-31-109-ENG-38 between the United States Government and the University of Chicago representing Argonne National Laboratory, and NIST 144 LM01, Subcontract No. AGT DTD 09/09/02.

FIELD

[0005] The present invention relates to electrolytes for use in electrochemical devices, and, more particularly to electrolytes including cyclic polysiloxanes.

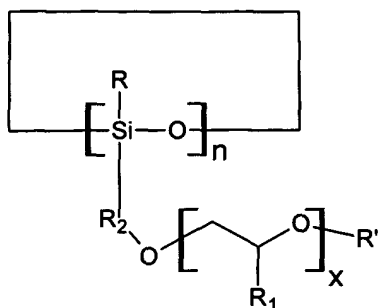
BACKGROUND

[0006] The demand for lithium secondary batteries to meet high power and high-energy system applications has resulted in substantial research and development activities to improve their safety, as well as performance. As the world becomes increasingly dependent on portable electronic devices, and looks toward increased use of electrochemical storage devices for vehicles, power distribution load leveling and the like, it is increasingly important that the safety of such devices be paramount, especially as these devices are being used in such environments as airliners and space vehicles. Similarly, safety for medical applications must be paramount. The effort to date has included research in flame-retardants, solid electrolytes, and new electrolyte concepts with improved thermostability. Thus, the development of highly conductive electrolytes, free of problems associated with volatile and combustible solvents, is of paramount importance.

SUMMARY

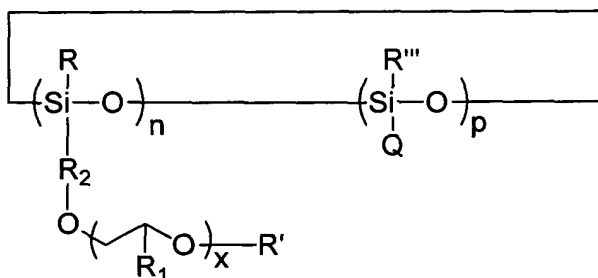
[0007] Disclosed is an electrolyte including a cyclic polysiloxane having one or more side-chains that each include a poly(alkylene oxide) moiety and a spacer. Each spacer is positioned between the poly(alkylene oxide) moiety and a silicon on the main chain of the polysiloxane.

[0008] In one aspect of the invention, the electrolyte is a liquid and the cyclic polysiloxane has a structure represented by the formula:



[0009] wherein R is an alkyl or aryl group; R' is an alkyl or aryl group; R₁ is hydrogen or an alkyl group; R₂ is a spacer made up of one or more CH₂ groups; n is from 1 to 100; and x is from 1 to 30.

[0010] In another aspect of the invention, the electrolyte is a solid and the cyclic polysiloxane has a structure represented by the formula:



[0011] wherein R is an alkyl group, R' is an alkyl or aryl group, R''' is alkyl or hydrogen; R₁ is hydrogen or an alkyl group; R₂ is a spacer made up of one or more CH₂ groups; p is greater than 0; n is from 1 to 100; x is from 1 to 30; and Q is a cross-linker linking the polysiloxane to another polysiloxane. Examples of the cross-linker represented by the Q include, but are not limited to, $-CH_2-CH_2-CH_2-R_3-CH_2-CH_2-CH_2-$, where R₃ is a moiety selected from the group consisting of $O-(CH_2CH_2O)_q$ and $Si-O-(Si-O)_k-Si$, where q is at least 4 and less than 30, and k is at least 5 and less than 30.

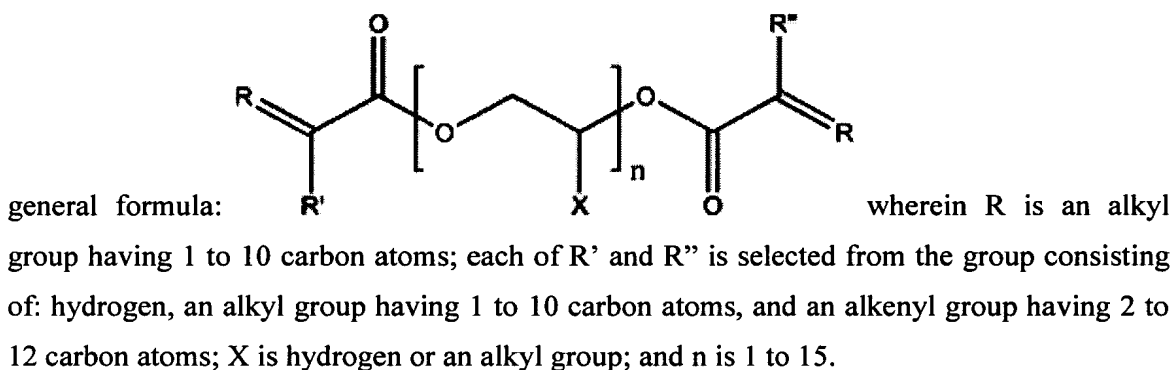
[0012] The cyclic polysiloxane can be synthesized so as to have an average molecular weight less than or equal to 3,000 g/mol. In some instances, the polysiloxane is synthesized so as to have a dynamic viscosity less than or equal to 2,000 cps or 10,000 cps.

[0013] The electrolyte can include a salt such as a lithium salt. Suitable lithium salts include, but are not limited to, LiClO₄, LiBF₄, LiAsF₆, LiPF₆, LiCF₃SO₃, Li(CF₃SO₂)₂N, Li(CF₃SO₂)₃C, LiN(SO₂C₂F₅)₂, lithium alkyl fluorophosphates, lithium bis(chelato)borates such as lithium bis(oxalato)borate (LiB(C₂O₄)₂), LiPF₃(C₂F₅)₃, and LiPF₃(CF₃)₃. In some

instances, the electrolyte includes a lithium bis(chelato)borate having 5 to 10 membered rings or 5 to 7 membered rings.

[0014] The electrolyte can include one or more network polymers. In some instances, the cyclic polysiloxane is entrapped within the network polymer. Although an electrolyte can be a liquid or a gel, the network forming polymer can serve to solidify the electrolyte. In some instances, the network polymer is a cross-linked polyacrylate, a cross-linked polymethacrylate, or a cross-linked polysiloxane.

[0015] In some instances, a precursor for forming the network polymer is represented by



[0016] The electrolyte can also include at least one solid polymer. In some instances, the solid polymer can serve to solidify the electrolyte. The at least one solid polymer can be selected from the group consisting of: polyacrylonitrile (PAN), poly(methyl methacrylate) (PMMA), poly(vinylidene fluoride) (PVdF), poly(vinylidene fluoride-co-hexafluoropropylene), poly(vinyl acetate), polystyrene, and poly(ethylene oxide) (PEO).

[0017] Also disclosed is a method for synthesizing a cyclic polysiloxane. The method includes mixing a cyclic polysiloxane precursor having at least a portion of the main chain silicons bonded to a hydrogen and an allyl terminated side-chain precursor that includes a poly(alkylene oxide) moiety. The polysiloxane and side-chain precursor are mixed so as to form a cyclic polysiloxane having one or more side-chains that each include a poly(alkylene oxide) moiety and a spacer positioned between the poly(alkylene oxide) moiety and a silicon on the main chain of the cyclic polysiloxane. In some instances, the side-chain precursor includes tri(ethyleneglycol) methyl ether.

[0018] The method can also include mixing a catalyst with the polysiloxane and the side-chain precursor. The catalyst can include platinum. In some instances, the catalyst includes dicyclopentadiene platinum(II) dichloride.

DESCRIPTION OF THE DRAWINGS

[0019] Figure 1 is a summary of the synthesis of one species of the cyclic polysiloxane of present invention.

[0020] Figure 2 is a plot of temperature vs. conductivity for cyclic poly(siloxane-g-3 ethylene oxide) electrolyte. LiTFSi was used as a lithium salt.

DETAILED DESCRIPTION

[0021] The invention relates to an electrolyte that includes a cyclic polysiloxane having one or more spacers that are each positioned between a main chain silicon and a poly(alkylene oxide) moiety. These polysiloxanes can be reasonably easy to synthesize and can provide an electrolyte with a high ionic conductivity near room temperature. Further, the polysiloxanes can coordinate with lithium salts and can often dissociate these salts. These polysiloxanes can be used in liquid electrolytes or in solid electrolytes. When these polysiloxanes are used in a liquid electrolyte, the choice of a cyclic structure can reduce the molecular weight and therefore lead to a decrease in viscosity and increase in Li-ion conductivity.

[0022] These polysiloxanes can be entrapped inside cross-linked polymer networks or mixed with solid polymers such as polyacrylonitrile (PAN), poly(methyl methacrylate) (PMMA), poly(vinylidene fluoride) (PVdF), poly(vinylidene fluoride-co-hexafluoropropylene), poly(vinyl acetate), polystyrene, poly(ethylene oxide) (PEO), etc. These polysiloxanes can also be employed in a cross-linked electrolyte solution.

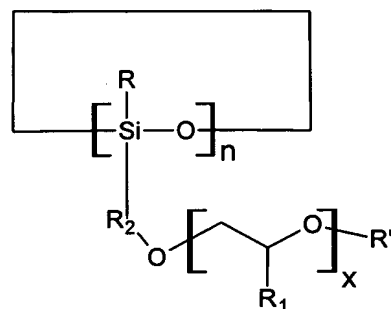
[0023] These polysiloxanes can also yield an electrolyte that is suitable for high-energy and long-life lithium primary and/or secondary batteries including, but not limited to, biomedical devices, electric and hybrid vehicles, consumer electronics, submarines, and

satellites. Further, the electrolytes of the present invention can be used in an electrochemical cell, providing enhanced shelf life and safety.

[0024] The electrolyte includes a cyclic polysiloxane having one or more side-chains that each include a poly(alkylene oxide) moiety and a spacer. Each spacer is positioned between the poly(alkylene oxide) moiety and a silicon on the main chain of the polysiloxane. The spacer can include one or more carbons. Further, the spacer can include one or more CH₂ groups.

[0025] The electrolyte can be a liquid. General Formula I represents examples of polysiloxane structures that are suitable for use in a liquid electrolyte. Formula I shows poly(ethylene oxide) serving as the poly(alkylene oxide) and a carbon based spacer. The cyclic polysiloxane main body can provide flame-retardant properties and chemical stability. The poly(ethylene oxide) moiety in the side chains can provide ionic conduction. Suitable methods for synthesizing these polysiloxanes include, but are not limited to, dehydrogenation using mild catalysts such as aryl borate or potassium carbonate, or hydrosilylation using platinum complex catalysts such as Pt(dvs) or (dicyclopentadiene) PtCl₂.

[0026] General Formula I:



[0027] wherein R is an alkyl or aryl group; R' is an alkyl or aryl group; R₁ is hydrogen or an alkyl group; R₂ is a spacer made up of one or more CH₂ groups; n is from 1 to 100; and x is from 1 to 30.

[0028] A liquid electrolyte can be formed by dissolving a salt in a liquid polysiloxane having a structure according to General Formula 1. The cyclic polysiloxane dissolves a variety of salts including, but not limited to, lithium salts and other salts that exclude lithium. Examples of lithium salts suitable for dissolving in the cyclic polysiloxane include, but are

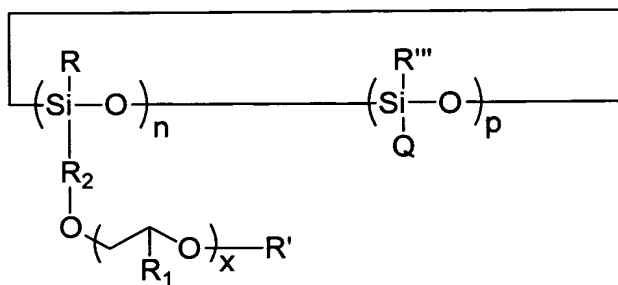
not limited to, LiClO_4 , LiBF_4 , LiAsF_6 , LiPF_6 , LiCF_3SO_3 , $\text{Li}(\text{CF}_3\text{SO}_2)_2\text{N}$, $\text{Li}(\text{CF}_3\text{SO}_2)_3\text{C}$, $\text{LiN}(\text{SO}_2\text{C}_2\text{F}_5)_2$, lithium alkyl fluorophosphates, lithium bis(oxalato)borate ($\text{LiB}(\text{C}_2\text{O}_4)_2$), as well as other lithium bis(chelato)borates having five to seven membered rings, $\text{LiPF}_3(\text{C}_2\text{F}_5)_3$, $\text{LiPF}_3(\text{CF}_3)_3$, and mixtures thereof. The polysiloxane can have enough flexibility to transport the lithium ions that result from dissolving the salt. As a result, the polysiloxane is suitable for use in the electrolytes of electrochemical devices such as batteries and capacitors.

[0029] The electrolyte is preferably synthesized with an $[\text{EO}]/[\text{Li}]$ ratio of 5 to 50. In determining the $[\text{EO}]/[\text{Li}]$ ratio, $[\text{EO}]$ is the molar concentration in the electrolyte of the active oxygens in the one or more siloxane polymers. Because $[\text{EO}]$ is directed to active oxygens, there are $x+1$ oxygens in each side chain constructed according to Formula I. $[\text{Li}]$ is the molar concentration of the lithium in the electrolyte. If the $[\text{EO}]/[\text{Li}]$ ratio is larger than 50, the ionic conductivity of the resulting polymeric electrolyte can decrease undesirably because of the inadequate numbers of carrier ions in the electrolyte. If the $[\text{EO}]/[\text{Li}]$ ratio is smaller than 5, the salt may not sufficiently dissociate and the aggregated lithium ions can reduce the ionic conductivity. A suitable average molecular weight for cyclic polysiloxanes having a structure according to General Formula I includes, but is not limited to, an average molecular weight less than or equal to 3,000 g/mole.

[0030] The electrolyte can include one or more other polysiloxanes blended with the cyclic polysiloxane. Different polysiloxanes in the blend can be selected to provide different functions. For instance, a polysiloxane according to General Formula I may provide the electrolyte with a high degree of voltage stability while other polysiloxanes in the blend may provide the electrolyte with a high degree of ionic conductivity. Examples of polysiloxanes that are particularly suitable for combining with a cyclic polysiloxane according to General Formula I are taught in PCT application number PCT/US03/08779, entitled "Polymer Electrolyte for Electrochemical Cell" and filed March 20, 2003 which claims priority to U.S. Provisional Patent Application serial number 60/446,848, entitled "Polymer Electrolyte for Electrochemical Cell" and filed February 11, 2003 each of which are incorporated by reference herein in its entirety.

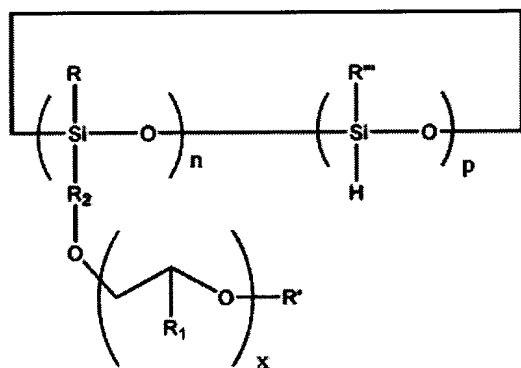
[0031] The cyclic polysiloxane can also be employed in a solid or gel electrolyte. For instance, the cyclic polysiloxane can be cross-linked so as to form a solid or a gel. Examples

of polysiloxane structures that are suitable for use in a solid and/or gel electrolyte are represented by General Formula II:



wherein R is an alkyl group, R' is an alkyl or aryl group, R''' is alkyl or hydrogen; R₁ is hydrogen or an alkyl group; R₂ is a spacer made up of one or more CH₂ groups; p is greater than 0; n is from 1 to 100; x is from 1 to 30; and Q is a cross-linker that links the main chain of one polysiloxane to the main chain of another polysiloxane.

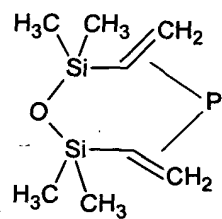
[0032] A polysiloxane having a structure according to General Formula II can be synthesized by employing a hydrosilylation reaction between Si-H bonds on a precursor polysiloxane and an allyl terminated cross-linking agent. Examples of polysiloxane structures that are suitable for use as a precursor polysiloxane in the hydrosilylation reaction are represented by General formula III:



[0033] wherein R is an alkyl group; R' is an alkyl or aryl group; R''' is alkyl or hydrogen; R₁ is a hydrogen or an alkyl group; R₂ is a spacer made up of one or more CH₂ groups; p is greater than 0; n is from 1 to 100; and x is from 1 to 30. The hydrogen bonded silicons can serve as cross-linker binding sites during the hydrosilylation reaction. Suitable ratios of p:n include, but are not limited to, ratios in a range of 1:6 to 1:1. The hydrogen-bonded silicons need not be positioned adjacent to one another along the main chain but can be distributed among the silicons bonded to side chains.

[0034] Suitable cross-linking agents for use in the hydrosilylation reaction include, but are not limited to, compounds terminated with two or more allyl groups. Examples of suitable cross-linking agents include diallyl-terminated siloxane, diallyl terminated polysiloxanes, diallyl terminated alkylene glycols, and diallyl terminated poly(alkylene glycol)s. Examples of suitable cross-linking agents can be represented by the formula, $\text{CH}_2=\text{CH}-\text{CH}_2-\text{R}_3-\text{CH}_2-\text{CH}=\text{CH}_2$, where R_3 is a moiety selected from the group consisting of $\text{O}-(\text{CH}_2\text{CH}_2\text{O})_q$ and $\text{Si}-\text{O}-(\text{Si}-\text{O})_k-\text{Si}$, where q is at least 4 and less than 30, and k is at least 4 and less than 30. These cross-linking agents can be generated as disclosed in U.S. patent application serial number 10/367,013, filed February 13, 2003, entitled "Cross-linked Polysiloxanes" and incorporated herein in its entirety. When these cross-linking agents are employed to cross-link a polysiloxane having a portion of the main chain silicons bonded to a hydrogen, the Si-H bonds in the main chain of the polysiloxane are replaced with a bond between the silicon and a terminal carbon on the cross-linking agent. Accordingly, examples of the cross-linker represented by the Q in Formula II can be represented by the formula, $-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{R}_3-\text{CH}_2-\text{CH}_2-\text{CH}_2-$, where R_3 is a moiety selected from the group consisting of $\text{O}-(\text{CH}_2\text{CH}_2\text{O})_q$ and $\text{Si}-\text{O}-(\text{Si}-\text{O})_k-\text{Si}$, where q is at least 4 and less than 30, and k is at least 5 and less than 30.

[0035] A solid electrolyte having a cross-linked polysiloxane can be formed by mixing the polysiloxane precursor and the cross-linking agent in a precursor solution. In some instances, a solvent may also be added to the precursor solution. Suitable solvents include, but are not limited to, tetrahydrofuran (THF). One or more of the salts discussed above can be added to the precursor solution. The one or more salts can be added directly or can be included in the solvent or other component of the precursor solution. In some instances, a catalyst is added to the precursor solution to react the polysiloxane precursor with the cross-linking agent. Suitable catalysts include, but are not limited to, platinum catalysts such as Karstedt's catalyst, dicyclopentadiene platinum(II) dichloride and H_2PtCl_6 . Karstedt's



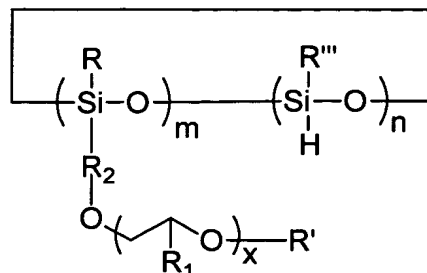
catalyst has a structure represented by the following formula: . These catalysts are mentioned by way of example and are not intended to limit the scope of potential catalysts. In some instances, a cross-linking inhibitor is added to the precursor

solution to slow the reaction enough to permit handling prior to the viscosity changing. Suitable inhibitors include, but are not limited to, dibutyl maleate. In some instances, vacuum can be applied to the precursor solution to remove solvent and/or trace moisture. The vacuum may be applied during and/or after formation of the precursor solution. Additionally, heat is applied to the precursor solution to react the polysiloxane precursor with the cross-linking agent and to convert the precursor solution to a solid or to a gel electrolyte.

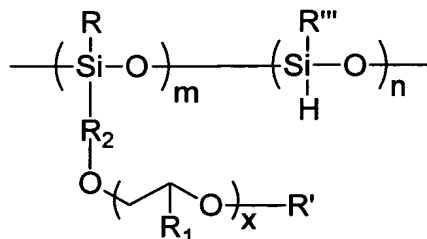
[0036] Another embodiment of a solid electrolyte includes a network polymer in addition to the cyclic polysiloxane. In some instances, a cyclic polysiloxane having a structure according to General Formula I and/or General Formula II is entrapped within the network polymer. An electrolyte including a networking polymer can often be converted from a liquid to a solid or a gel. Accordingly, an electrolyte including a network polymer can be a solid, a gel, or a liquid.

[0037] A polysiloxane can serve as the network polymer. In some instances, a network polysiloxane can enhance ionic conductivity and/or stability. Suitable network polysiloxanes can be formed from a precursor polysiloxane having n of the main chain silicons bonded to a hydrogen and m of the main chain silicons bonded to a side chain. The side chains can include a poly(alkylene) moiety or an oligo(alkylene) moiety. Suitable poly(alkylene)s include, but are not limited to, poly(ethylene). Suitable oligo(alkylene)s include, but are not limited to, oligo(ethylene)s. Suitable ratios for the number of n silicons to the number of m silicons include, but are not limited to, ratios in a range of 1:4 to 1:200, in a range of 1:6 to 1:100, or in a range of 1:6 to 1:70. The hydrogen-bonded silicons need not be positioned adjacent to one another along the main chain but can be distributed among the silicons bonded to side chains.

[0038] A suitable precursor polysiloxane for use in forming a network polymer can be linear or cyclical. An example of a cyclical precursor polysiloxane is represented by General Formula IV and example of a linear precursor polysiloxane is represented by General Formula V.

[0039] General Formula IV:

[0040] wherein R is an alkyl group; R' is an alkyl or aryl group; R''' is an alkyl group or a hydrogen; R₁ is hydrogen or an alkyl group; R₂ is a spacer made up of one or more CH₂ groups; n is greater than 0; m is from 1 to 100; and x is from 1 to 30.

[0041] General Formula V:

[0042] wherein R is an alkyl group; R' is an alkyl or aryl group; R''' is an alkyl group or a hydrogen; R₁ is a hydrogen or an alkyl group; R₂ is a spacer made of one or more CH₂ groups; m is from 1 to 100; n is greater than 0; and x is from 1 to 30.

[0043] A precursor polysiloxane having a portion of the main chain silicons bonded to a hydrogen can be reacted with a cross-linking agent to generate a cross-linked polysiloxane suitable for serving as a network polymer. Suitable cross-linking agents include, but are not limited to, compounds terminated with two or more allyl groups. Examples of suitable cross-linking agents include diallyl-terminated siloxane, diallyl terminated polysiloxanes, diallyl terminated alkylene glycols, and diallyl terminated poly(alkylene glycol)s. Suitable cross-linking agents can be represented by the formula, CH₂=CH-CH₂-R₃-CH₂-CH=CH₂, where R₃ is a moiety selected from the group consisting of O-(CH₂CH₂O)_q and Si-O-(Si-O)_k-Si, where q is at least 4 and less than 30, and k is at least 5 and less than 30. These cross-linking agents can be generated as disclosed in U.S. patent application serial number 10/367,013, filed February 13, 2003, entitled "Cross-linked Polysiloxanes" and incorporated herein in its

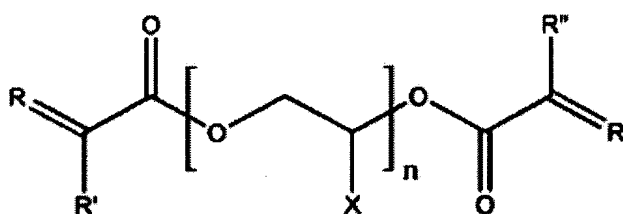
entirety. When these cross-linking agents are employed to cross-link a precursor polysiloxane, the Si-H bonds in the main chain of the polysiloxane are replaced with a bond between the silicon and a terminal carbon on the cross-linking agent. Accordingly, the cross-linker that results from these cross-linking agents can be represented by the formula, $-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{R}_3-\text{CH}_2-\text{CH}_2-\text{CH}_2-$, where R_3 is a moiety selected from the group consisting of $\text{O}-(\text{CH}_2\text{CH}_2\text{O})_q$ and $\text{Si-O}-(\text{Si-O})_k-\text{Si}$, where q is at least 4 and less than 30, and k is at least 5 and less than 30.

[0044] When the electrolyte is to include one or one more network polysiloxanes in addition to the cyclic polysiloxane, the one or more network polysiloxanes can be cross-linked before the cyclic polysiloxane is blended with the network polysiloxane. Alternatively, the network polysiloxane can be cross-linked in the presence of the cyclic polysiloxane. Additionally, the one or more network polysiloxanes can be cross-linked and one or more cyclic polysiloxanes can be polymerized in the presence of one another.

[0045] An example of a method for forming a solid electrolyte having a cyclic polysiloxane entrapped within a network polymer includes mixing a cyclic polysiloxane, the polysiloxane precursor and the cross-linking agent in a precursor solution. In some instances, a solvent may also be added to the precursor solution. Suitable solvents include, but are not limited to, THF. One or more of the salts discussed above can be added to the precursor solution. The one or more salts can be added directly to the precursor solution or can be included in the solvent or in another component of the precursor solution. In some instances, a catalyst is added to the precursor solution to react the polysiloxane precursor with the cross-linking agent. Suitable catalysts include, but are not limited to, platinum catalysts. These catalysts are mentioned by way of example and are not intended to limit the scope of potential catalysts. In some instances, a cross-linking inhibitor is added to the precursor solution to slow the reaction enough to permit handling prior to the viscosity changing. Suitable inhibitors include, but are not limited to, dibutyl maleate. In some instances, vacuum applied to the precursor solution to remove solvent and/or trace moisture. Additionally, heat can applied to the precursor solution to react the polysiloxane precursor with the cross-linking agent. The reaction of the polysiloxane precursor with the cross-linking agent forms the network polymer and converts the precursor solution to a solid or to a gel electrolyte.

[0046] The network polymer need not be a polysiloxane. For instance, other examples of network polymers include, but are not limited to, cross-linked polyacrylates and cross-linked polymethacrylates. Suitable precursors for forming the network polymer include, but are not limited to, acrylates and methacrylates. Acrylates and/or methacrylates having two or more functionalities can both polymerize and cross-link to form a cross-linked polyacrylate network polymer and/or to form a cross-linked polymethacrylate network polymer. In some instances, acrylates and/or methacrylates having four or more functionalities are a preferred network monomer. Suitable acrylates include, but are not limited to, poly(alkylene glycol) diacrylate. Suitable methacrylates include, but are not limited to, poly(alkylene glycol) dialkylacrylates such as poly(ethylene glycol) dimethacrylate. Other suitable poly(alkylene glycol) dialkyl alkyl acrylates are represented by Formula VII.

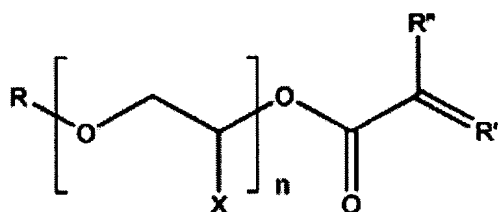
[0047] Formula VII:



wherein R represents a group selected from an alkyl group having 1 to 10 carbon atoms; R' represents hydrogen or an alkyl group having 1 to 10 carbon atoms or an alkenyl group having 2 to 12 carbon atoms; R'' represents hydrogen or an alkyl group having 1 to 10 carbon atoms or an alkenyl group having 2 to 12 carbon atoms; X represents hydrogen or an alkyl group, preferably a methyl group; and n is 1 to 15.

[0048] When a cross-linking network monomer is employed to form the network polymer, a control monomer can be employed to control cross-linking density. Formula VIII represents a suitable control monomer for use with a network monomer constructed according to Formula VII.

[0049] Formula VIII:



where R represents an alkyl group having 1 to 10 carbon atoms; R' represents an alkyl group having 1 to 10 carbon atoms; and R'' represents hydrogen or a group selected from an alkyl group having 1 to 10 carbon atoms and/or an alkenyl group having 2 to 12 carbon atoms; X represents a hydrogen or a methyl group; and n represents a whole number from 1 to 20.

[0050] An example of a method for forming an electrolyte that includes a network polymer in addition to the cyclic polysiloxane includes mixing the cyclic polysiloxane, monomers for forming one or more network polymers, one or more radical initiators, and one or more salts so as to form a precursor solution. Suitable radical initiators include, but are not limited to, thermal initiators including azo compounds such as azoisobutyronitrile, peroxide compounds such as benzoyl peroxide, and bismaleimide. In some instances, a control monomer is also added to the precursor solution to control the cross-linking density of the network monomer.

[0051] Electrolytes that include a network polymer and/or that include a cross-linked cyclic polysiloxane can often be solidified by providing sufficient heat to allow the initiator and/or a catalyst to begin working. In some instances, the electrolyte is solidified by heating to a temperature greater than 75°C. Accordingly, these electrolytes can often be solids. When a solid electrolyte is desired, a film of a precursor solution can be formed on a substrate. Suitable substrates include, but are not limited to, porous media and/or a substrate of an electrode for use in an electrochemical device such as a battery. Suitable porous media can serve as a separator in an electrochemical cell and include, but are not limited to, polyolefin separators, nonwoven separator, and polycarbonate separator. In some instances, the film on the substrate and/or the porous media can be heated to initiate cross-linking and solidify the electrolyte.

[0052] In some instances, the network polymer forms an interpenetrating network with the cyclic polysiloxane. An electrolyte having an interpenetrating network can be formed by

the interpenetrating network polymerization method taught in U.S. Patent application serial number 10/104,352, filed on March 22, 2002, entitled "Solid Polymer Electrolyte and Method of Preparation" and incorporated herein in its entirety. An electrolyte having an interpenetrating network can be formed by polymerizing and/or cross-linking one or more network polymers in the presence of the cyclic polysiloxane. Alternately, an electrolyte having an interpenetrating network can be formed by polymerizing and/or cross-linking the cyclic polysiloxane in the presence of the network forming monomer or monomers. Alternately, electrolyte having an interpenetrating network can be formed by polymerizing and/or cross-linking the cyclic polysiloxane and the network forming monomer in the presence of one another.

[0053] In an interpenetrating network formed using the monomers represented by Formula VII, the network polymer is formed from a monomer that cross-links. A network polymer suitable for the interpenetrating network can be formed using other precursors. For instance, the network polymer can be formed from monomers and cross-linking agents that are different from one another. Further, the monomers can heteropolymerize.

[0054] Other examples of methods of forming an interpenetrating network and electrochemical cells including electrolytes with interpenetrating network are described in U.S. Patent application serial number 10/104,352, filed on March 22, 2002, entitled "Solid Polymer Electrolyte and Method of Preparation" and incorporated herein in its entirety.

[0055] Further, the electrolyte can include a solid polymer that serves to solidify the electrolyte. The cyclic polysiloxane and the solid polymer can be formed before being mixed together. Alternatively, the cyclic polysiloxane can be formed in the presence of the solid polymer and/or the solid polymer can be formed in the presence of the cyclic polysiloxane. Examples of suitable solid polymers include, but are not limited to, polyacrylonitrile (PAN), poly(methyl methacrylate) (PMMA), poly(vinylidene fluoride) (PVdF), poly(vinylidene fluoride-co-hexafluoropropylene), poly(vinyl acetate), polystyrene, and poly(ethylene oxide) (PEO).

[0056] EXAMPLES

[0057] Example 1: A cyclic polysiloxane was synthesized according to Figure 1 with n equal to 4. The cyclic polysiloxane was synthesized using a platinum complex catalyst as follows: To a 250-mL flame-dried flask was added 1,3,5,7-tetramethylcyclotetrasiloxane (D_4^H) (Gelest, 12.0 g, 0.20 mol Si-H group), allyl terminated tri(ethyleneglycol) methyl ether (48.96 g, 0.24 mol, 20% excess) under nitrogen atmosphere. The heterogeneous mixture was stirred vigorously, and 30 μ l platinum divinyltetramethyldisiloxane (Pt(dvs)) (Aldrich, 3% solution in xylene) was injected into the mixture using a syringe and the temperature was gradually raised to 70-75°C. The reaction mixture was continuously stirred at this temperature for about 24 hours until no Si-H signal (4.7 ppm) was detected on ^1H -NMR spectrum. After excess allyl terminated tri(ethyleneglycol) methyl ether and its isomer were removed by Kugelrohr distillation by heating to about 120°C in a reduced atmospheric pressure of about 0.1 torr, the liquid was measured by FTIR which showed no Si-H and monomer peaks.

[0058] Figure 2 shows an ionic conductivity versus temperature curve for an electrolyte having the cyclic polysiloxane of Example 1 (wherein $n=4$, $p=0$, R and $R'=\text{CH}_3$, $R_2 = \text{CH}_2\text{CH}_2\text{CH}_2$) and $\text{LiN}(\text{SO}_2\text{CF}_3)$ mixed at a ratio of $[\text{EO}]/[\text{Li}] = 32:1$, where $[\text{EO}]$ is the number of oxygen atom in the PEO chains. The ionic conductivities were determined from AC impedance curves of 2032 button cells assembled by injecting the electrolyte between two stainless steel discs with a Teflon O-ring (1/32 inch thick) to prevent short circuits. The measurement frequency range was from 1 MHz to 100 Hz. The electrolyte shows an ionic conductivity of about $1.13 \times 10^{-4} \text{ S/cm}$ near 25°C and increased conductivity with increased temperature.

[0059] Example 2: A cyclic polysiloxane was synthesized according to Figure 1 with n equal to 5. The polysiloxane was synthesized with the same procedure as Example 1, a platinum catalyst and different precursors as follows: To a 250-mL flame-dried flask was added 1,3,5,7,9-pentamethylcyclopentasiloxane (D_5^H) (Gelest Inc., 24.0 g, 0.40 mol Si-H group), allyl terminated tri(ethylene glycol) methyl ether (97.92 g, 0.48 mol, 20% excess), and 60 μ l platinum divinyltetramethyldisiloxane Pt(dvs) (Aldrich Chem. Co., 3% solution in xylene).

[0060] Example 3: A cyclic polysiloxane was synthesized according to Figure 1 with n equal to 4. The polysiloxane was synthesized using the same procedure and precursors as for Example 1 and a different catalyst as follows: To a 250-mL flame-dried flask was added 1,3,5,7-tetramethylcyclotetrasiloxane (D_4^H) (Gelest, 12.0 g, 0.20 mol Si-H group), allyl terminated tri(ethylene glycol) methyl ether (44.88 g, 0.22mol, 10% excess) and 100 μ l dicyclopentadiene platinum(II) dichloride (white powder from Strem Chemicals, Inc., 3% solution in dichloromethane made in the lab).

[0061] Example 4: A solid electrolyte could be prepared so as to include the cyclic polysiloxane of Example 1 entrapped in a network polymer synthesized from poly(alkylene glycol) dimethacrylate. A precursor solution would be prepared by mixing the cyclic polysiloxane, a poly(ethylene glycol) dimethacrylate, a control monomer according to General Formula VIII, benzoyl peroxide, and $\text{LiN}(\text{SO}_2\text{CF}_3)_2$ (LiTFSI). A solid electrolyte could be formed by curing the precursor solution at 70°C for 2 hrs. This synthesis procedure is modeled after the interpenetrating polymerization technique described in detail in U. S. Patent Application serial number 10/104,352, filed on March 22, 2002, entitled "Solid Polymer Electrolyte and Method of Preparation" and incorporated herein by reference in its entirety.

[0062] Example 5: A stable electrolyte having an interpenetrating network could be prepared so as to entrap the cyclic polysiloxane of Example 1 inside a network polysiloxane. A precursor solution would be prepared by mixing the cyclic polysiloxane, a linear precursor polysiloxane having a structure according to General Formula V, a compound terminated with two or more allyl groups, a platinum catalyst, and a salt. The network polysiloxane could be formed by reacting the linear precursor polysiloxane with the allyl-terminated compound, using a hydrosilylation reaction as disclosed in U.S. patent application serial number 10/367,013, filed February 13, 2003, entitled "Cross-linked Polysiloxanes" as described above. In the linear precursor for this example, R is an alkyl group; R' is an alkyl or an aryl group; R'' is an alkyl group or a hydrogen; R₁ is an alkyl group or a hydrogen; R₂ is a spacer made up of one or more CH₂ groups; m is from 1 to 100; n is greater than 0; and x is from 1 to 30. The compound terminated with two or more allyl groups may comprise a compound such as a diallyl terminated poly(alkylene glycol) or diallyl terminated polysiloxane. The final interpenetrating network polymer electrolyte would be synthesized as was outlined in Example 4.

[0063] Example 6: A cyclic polysiloxane was prepared having a structure according to General Formula III with R, R' and R''' as methyl groups, R₁ as hydrogen; R₂ as a spacer including three CH₂ groups; x as 3; and n + p of 4 with an approximate n:p ratio on the order of 1:1.

[0064] To a 50-mL three-necked flame-dried flask was added 7.5 g of distilled 1,3,5,7-tetramethylcyclotetrasiloxane (D_4^H) (Gelest, 12.0 g, 0.125 mol Si-H bonds). A 20 mL syringe was employed to inject 12.75 g of tri(ethyleneglycol) allyl methyl ether (0.0625 mol) into the flask. The reaction system was filled with dry N₂ and heated to about 60 °C. 20 µL solution of platinum divinyltetramethyldisiloxane (Pt(dvs)) (Aldrich, 3% solution in xylene) was syringed into the above mixture. The result was stirred for about 12 hours until tri(ethyleneglycol) allyl methyl ether was not evident by ¹H-NMR. The result was vacuum distilled to remove isomers formed during the hydrosilylation.

[0065] Example 7: The cyclic polysiloxane of Example 6 was cross-linked. The polysiloxane generated according to Example 6 (2.0g, 6.16x10⁻³ mol Si-H bonds), 2.09 g of diallyl terminated poly(ethylene glycol) cross-linking agent (APEO13A, 3.08 x 10⁻³ mol), and 6 µL of dicyclopentadiene platinum(II) dichloride (3% in dichloromethane) were mixed in a 10 ml flask. The result was put under vacuum to remove moisture and then placed in an 80°C oven. After about 12 hours in the oven, the result was gelled into a solid cross-linked polysiloxane.

[0066] Example 8: A cyclic polysiloxane was prepared having a structure according to General Formula III with R, R', and R''' as methyl groups; R₁ as hydrogen; R₂ as a spacer including three CH₂ groups; ; x as 3; and n + p of 5 with an approximate n:p ratio on the order of 5:3.

[0067] To a 100-mL three-necked flame-dried flask was added 15 g of distilled 1,3,5,7,9-pentamethylcyclopentasiloxane (D_5^H) (Gelest, 0.25 mol Si-H bonds). A 20-mL syringe was employed to inject 30.6 g of tri(ethyleneglycol) allyl methyl ether (0.15 mol) into the flask. The reaction system was filled with dry N₂ and heated to about 60°C. 20 µL solution of platinum divinyltetramethyldisiloxane (Pt(dvs)) (Aldrich, 3% solution in xylene) was syringed into the above mixture. The result was stirred for about 12 hours until

tri(ethyleneglycol) allyl methyl ether was not evident by $^1\text{H-NMR}$. The result was vacuum distilled to remove isomers formed during the hydrosilylation.

[0068] Example 9: The cyclic polysiloxane of Example 8 was cross-linked. The polysiloxane generated according to Example 8 (1.0g, 2.19×10^{-3} mol Si-H bonds), 0.7454 g of diallyl terminated poly(ethylene glycol) cross-linking agent (APEO13A, 1.09×10^{-3} mol), and 10 μL of platinum divinyltetramethyldisiloxane (Pt(dvs)) (Aldrich, 3% solution in xylene) were mixed in a 10-ml flask. The result was put under vacuum to remove moisture and then placed in an 80°C oven. After about 16 hours in the oven, the result was gelled into a solid cross-linked polysiloxane.

[0069] Example 10: A cyclic polysiloxane was cross-linked so as to provide a polysiloxane according to General Formula II with R, R' and R''' as methyl groups; R_1 as hydrogen; R_2 as a spacer made up of three CH_2 groups; x of 3; p + n of 5; a p:n ratio of 2.8:2.2; and Q as $-\text{CH}_2-\text{CH}_2-\text{CH}_2-\text{R}_3-\text{CH}_2-\text{CH}_2-\text{CH}_2-$ with R_3 as $\text{O}-(\text{CH}_2\text{CH}_2\text{O})_q$ and q as 13. The cyclic polysiloxane was synthesized using a hydrosilylation reaction between a precursor polysiloxane and an allyl terminated cross-linking agent. The precursor polysiloxane had a structure according to General Formula III with R, R' and R''' as methyl groups; R_1 as hydrogen; R_2 as a spacer made up of three CH_2 groups; p + n of 5; and a ratio of p:n of 2.8:2.2.

[0070] The polysiloxane precursor (2.0g, 5.05×10^{-3} mol Si-H) was added into a dry 50 mL flask. Diallyl poly(ethylene glycol) cross-linker (q ~13) (1.72g, 2.52×10^{-3} mol), $\text{LiN}(\text{CF}_3\text{SO}_2)_2$ (3.05×10^{-3} mol, 38 mL of 0.0805mol/L THF solution) and dicyclopentadiene platinum (II) dichloride (200 μL 7.5×10^{-3} M CH_2Cl_2 solution) were syringed into the flask, and a clear solution was obtained. A vacuum was pulled on the solution for 12 h and then the solution was further evacuated on a high-vacuum line ($\sim 10^{-5}$ torr) for 48 h to completely remove the THF. The flask was sealed and transferred into a glove-box, where the viscous mixture was loaded into the conductivity measurement cell. After at least 2 h in an 80°C oven, a solid gel resulted. IR does not show any Si-H absorbance at 2100 cm^{-1} area, indicating that the cross-linking reaction is complete.

[0071] Example 11: A cyclic polysiloxane was cross-linked so as to provide a polysiloxane according to General Formula II with R, R' and R''' as methyl groups; R_1 as

hydrogen; R_2 as a spacer made up of three CH_2 groups; x of 3; $p + n$ of 5 and a $p:n$ ratio of 3.2:1.8 and Q as $-\text{CH}_2-\text{CH}_2-\text{CH}_2-R_3-\text{CH}_2-\text{CH}_2-\text{CH}_2-$ with R_3 as $\text{O}-(\text{CH}_2\text{CH}_2\text{O})_q$ and q of 13. The cyclic polysiloxane was synthesized using a hydrosilylation reaction between a precursor polysiloxane and an allyl terminated cross-linking agent. The precursor polysiloxane had a structure according to General Formula III with R , R' and R'' as methyl groups; R_1 as hydrogen; R_2 as a spacer made up of three CH_2 groups; $p + n$ of 5; and a ratio $p:n$ of 3.2:1.8.

[0072] The polysiloxane precursor (2.0g , 5.05×10^{-3} mol Si-H) was added into a dry 50 mL flask. Diallyl poly(ethylene glycol) cross-linking agent (1.72g , 2.52×10^{-3} mol), $\text{LiN}(\text{CF}_3\text{SO}_2)_2$ (3.05×10^{-3} mol, 38 mL of 0.0805 mol/L THF solution) and dicyclopentadiene platinum (II) dichloride ($200\text{ }\mu\text{L}$ $7.5 \times 10^{-3}\text{ M}$ CH_2Cl_2 solution) were syringed into the flask, and a clear solution was obtained. A vacuum was pulled on the solution for 12 h and then the solution was further evacuated on a high-vacuum line ($\sim 10^{-5}$ torr) for 48 h to completely remove the THF. The flask was sealed and transferred into a glove box where the viscous mixture was loaded into the conductivity measurement cell. After at least 2 h in an 80°C oven, a solid gel resulted. IR does not show any Si-H absorbance at 2100 cm^{-1} area, indicating that the cross-linking reaction is complete.

[0073] Although the electrolyte is disclosed in the context of an electrolyte having a single cyclic polysiloxane, the electrolyte can include a plurality of cyclic polysiloxanes having different structures.

[0074] The electrolytes described above can be applied in electrochemical devices such as batteries and capacitors in the same way as common carbonate-based electrolytes and other polysiloxane based electrolytes. In some instances, the electrolytes are employed in lithium secondary batteries solutions. Lithium secondary batteries employing the above electrolytes can be fabricated by injecting the polymeric electrolyte solution into a spiral wound cell or prismatic type cell (laminated, Z-fold, etc.). It can also be coated onto the surface of electrodes and assembled with a porous separator to fabricate a single or multi-stacked cell that is packaged in a plastic or plastic/foil laminated pouch. Additionally, the electrolyte of the present invention can be mixed with the active material, the binder, and the electronic additive (a conductor typically made from graphite, carbon black, acetylene black, or other carbonaceous material) to form a slurry and then cast the slurry with an embedded current collector to obtain a composite electrode after drying.

[0075] Although many of the electrolyte features such as salt concentrations and molecular weights are described in the context of a liquid electrolyte, these features can also be applied to solid electrolytes as well.

[0076] Other embodiments, combinations and modifications of this invention will occur readily to those of ordinary skill in the art in view of these teachings. Therefore, this invention is to be limited only by the following claims, which include all such embodiments and modifications when viewed in conjunction with the above specification and accompanying drawings.